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# Various battery models for various simulation studies and applications

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ABSTRACT

Batteries are one of the most common devices used for saving electrical energy in various applications. It is necessary to understand the battery behavior and performance during charge and discharge cycles. An accurate model of a battery with a specific application is needed for an appropriate analysis and simulation. Therefore, in the field of battery modeling, various models have been proposed. This paper presents an overview of several electrical battery models. These models are classified into six categories. The parameter details of a battery model will not be computed but a brief description of them is given. Furthermore, the applications of each model are discussed. Finally, a comparison between presented models will be made.



**Contents**



## 1. Introduction

Nowadays, energy storages have numerous applications. Batteries are the most famous of them. They are applied in several

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industries such as in electrical and hybrid vehicles [1–7], renewable energy systems [8–12], and marine current energy systems [13]. Batteries serve as a backup in wind energy conversion systems (WECS) or photovoltaic (PV) systems. They are implemented to store excess energy captured from wind energy or sunlight using wind turbines during windy or sunny days and also for releasing the stored energy during stationary times or at night time [8,9]. Another application of battery storage is in aerospace satellites. They are used to collect energy using PV panel for satisfying required energy when the satellite is exposed to the sun and to release the energy during eclipse [14]. In electric or hybrid trains and vehicles, a battery is used for storing energy from regenerative braking system and returning the energy to the system when the train is in traction mode [1–7]. Batteries can play a significant role when they used with other storages such as fuel cells, ultra-capacitors, and super-magnetic energy storages (SMES). They can increase reliability of the hybrid systems [15,16]. Various flexible AC transmission system (FACTS) devices such as dynamic voltage resistor (DVR), and static compensator (STATCOM) utilize a battery for improving power quality of electrical voltage such as voltage sags [17]. Furthermore, the battery accompanied by an inverter is implemented in an uninterruptible power supply (UPS) in order to satisfy the loads and burdens during voltage sag and power interruption [18]. In all the above mentioned applications, an accurate modeling and simulation of a battery for examining system performance is necessary. Battery modeling involves two categories of electrochemical modeling and electrical circuit modeling. The electrochemical model of a battery is structurally based on the internal electrochemical actions and reactions of a cell. It is not obtained from an electrical network. Although accurate, this model is complex and needs a precise recognition of the electrochemical processes in the cell. It is not applied in power and dynamic systems studies. Electrical circuit modeling is another useful model presented by many researchers. In the electrical circuit modeling, the electrical characteristics of the battery are considered and passive linear elements are used. Such models are easy to understand. For example, the battery capacity is modeled by a capacitor. Given that the voltage and internal resistance of a battery are dependent on temperature and state of charge, open circuit voltage of a battery represented by a controlled dc voltage source is changed by the state of charge and temperature. Moreover, internal resistance is modeled by variable resistance. The value of the internal resistance is changed by the state of charge and temperature as well. In this paper, the electrical circuit models are classified into six overall models. These models consist of simple models, Thevenin-based models, impedance-based models, runtime-based models, combined electrical circuit-based models, and generic-based models. Specifications and applications of each model are considered and discussed. Finally, advantages and disadvantages of each model are presented below.

## 2. Simple battery models

In this section, six simple-based models of a battery will be described briefly as follows.

### 2.1. Ideal battery model

The ideal battery model is the simplest model because the internal parameters are neglected. It is represented by only an ideal voltage source. This model is shown in Fig. 1 [19]. It is mainly suitable in some simulations where the energy released from the battery is supposed to be infinite. In this model, the state of charge and internal parameters of the battery are not considered. Furthermore, the application of this model is mainly in the simulation of slag bus in steady state studies of power systems.

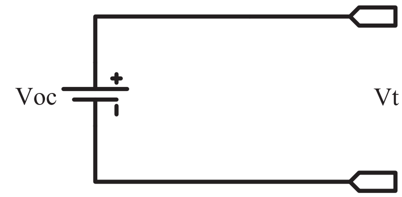


**Fig. 1.** Ideal battery model.

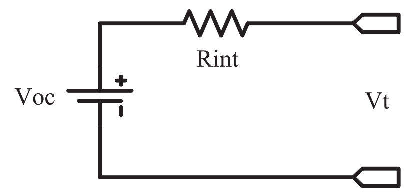


**Fig. 2.** Simple battery model.

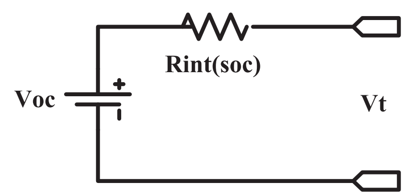


**Fig. 3.** Modified simple battery model 1.

### 2.2. Simple battery model

A simple battery model, shown in Fig. 2, is composed of a series of internal resistance connected to an ideal voltage source. State of charge (SOC) is not considered in this model. In this figure, $V_o$ is an ideal open-circuit voltage, $V_t$ is the terminal voltage of battery and $R_{int}$ is the internal series resistance. In the simple battery model, $V_t$ can be clarified by an open circuit voltage measurement test. $R_{int}$ is assumed to be constant while it is changed when a load is connected to a battery. Thus, this model is just appropriate in circuit simulations where the energy released from the battery is supposed to be infinite or the state of charge is not important [20]. For example, this model is not suitable for electric trains or vehicles application. However, it can be used with ultra-capacitor or fuel cell as hybrid energy storage. Also, this model is applied as an input source connected to the inverter power electronic devices [21].

### 2.3. Modified simple battery model 1

A model made up of an ideal voltage source accompanied by an internal resistance is discussed in [22]. Here, the voltage source and internal resistance are a function of the SOC. This model is shown in Fig. 3. In this battery model, the state of charge is considered by making the $R_{int}$ and $V_{oc}$ of battery changes in accordance with its state of charge. $R_{int}$ is determined through following equation:

$$R_{int} = \frac{R_0}{S^K} \tag{1}$$

where $S$ and $R_0$ are the state of charge and initial battery internal resistance respectively. $R_0$ is calculated when the battery is fully

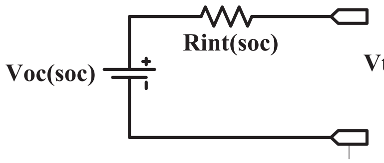


**Fig. 4.** Modified simple battery model 2.

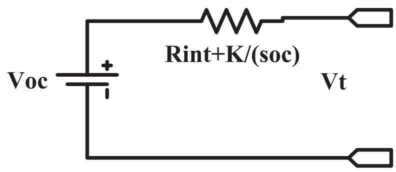


**Fig. 5.** Modified simple battery model 3.

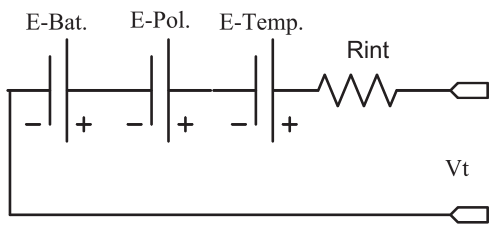


**Fig. 6.** Modified simple battery model 4.

charged:

$$S = 1 - \frac{Ah}{C_{10}} \quad (2)$$

In the above equation, $C_{10}$ is ten-hour capacity (Ampere–hours) at the reference temperature. $A$ and $h$ are the current and time of discharging process respectively. $S$ changes from 0 (when battery is discharged) to 1 (when battery is fully charged). $K$ is a constant designated capacity coefficient. It is related to discharge rate. It is computed based on $k_1$, $k_2$ and $k_3$. The coefficients of $k_1$, $k_2$ and $k_3$ are constants specified using the curves supplied by the manufacturers. They are related to three different charge rates. Furthermore, the capacity of the battery changes using the coefficient of $K$ under different discharge rates. This model has been applied by many battery manufacturers for battery monitoring aims. This model does not explain for the capacitance effect as an example of the transient current conditions taking place in the battery. It is used for modeling of a sealed lead acid battery applied in an uninterruptible power supply [23].

### 2.4. Modified simple battery model 2

In this model, shown in Fig. 4, the battery is used as a voltage source connected to a series resistance. The voltage and internal resistance are related to the state of charge (SOC). The open circuit voltage is described as

$$V_t = V_{oc}(SOC) - IR_{int}(SOC) \quad (3)$$

where $V_{oc}=f\,(SOC)$ is the no load voltage of the battery and $R_{int}=f(SOC)$ is the internal resistances of discharge and charge cycles, where

$$V_{oc} = V_o - A \cdot D \quad (4)$$

$$R_{int} = R_o - B \cdot D \quad (5)$$

where $V_o$ is open circuit voltage (battery is in full charge), $D$ is the state of discharge, $R_{int}$ is the internal resistance (battery is in full charge), and $A$, $B$ are constants obtained from experiments. This model does not account for the transient condition [24]. This model is applied in a single phase inverter system in order to generate an alternative voltage from a DC voltage for satisfying an AC load such as an induction motor.

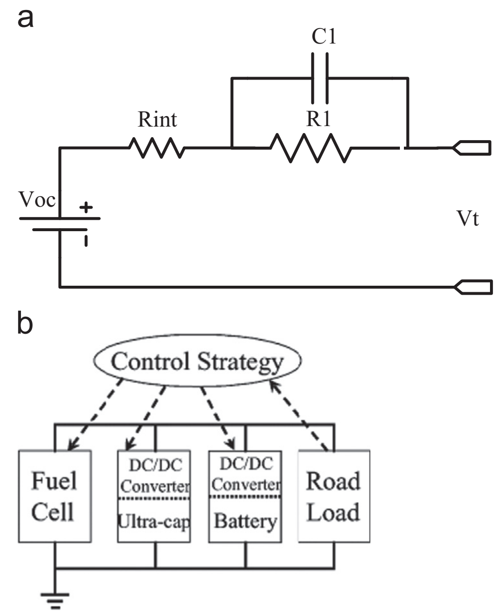


**Fig. 7.** (a) Thevenin battery model. (b) Hybrid of battery and fuel cell and ultra capacitor.

### 2.5. Modified simple battery model 3

The modified simple battery model 3, shown in Fig. 5, is developed based on the Thevenin battery model. The open circuit voltage and internal resistance are nonlinear characteristics indicated by $K/SOC$ [25]:

$$V_t = V_{oc} - \left(R_{int} + \frac{K}{SOC}\right)I \quad (6)$$

where $V_t$ is terminal voltage of battery, $V_{oc}$ is no load circuit voltage, $R_{int}$ is battery terminal resistance, $K$ is polarization constant, and $I$ is discharge current. This model is implemented in the modeling of lead acid battery used in traction systems [25].

### 2.6. Modified simple battery model 4

This model, shown in Fig. 6, is structurally based on three voltage sources and an internal resistance. Each element modeled in PSPICE software is described as follows:

(1) E-bat. (E-Battery): This is an ideal voltage source that displays the voltage in the cells.
(2) E-pol. (E-polarization): It shows the effects of polarization caused by the active materials availability in the battery.
(3) E-Temp. (E-Temperature): It displays the temperature effect on the terminal voltage of the battery.
(4) Rint. (Internal Resistance): This is the internal impedance of the battery.

The value of each element is dependent on the relationship between voltage and the state of charge of the battery cell. This model is relatively accurate and can be used for Ni–Cd and Li-ion batteries and applied in the charge and discharge cycles. Also, it could be applied to traction applications or electric/hybrid vehicles [26].

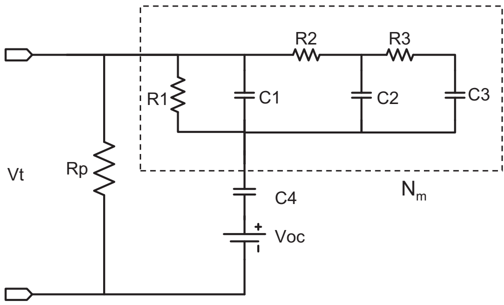


**Fig. 8.** Modified Thevenin battery model 1.

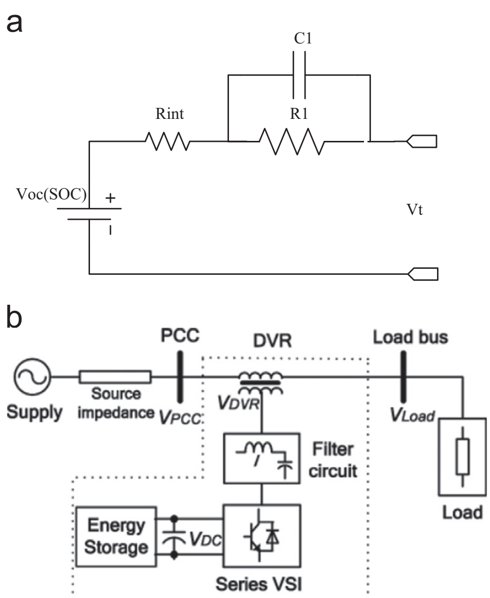


**Fig. 9.** (a) Thevenin battery model 2. (b) Battery storage applied in a dynamic voltage resistor.

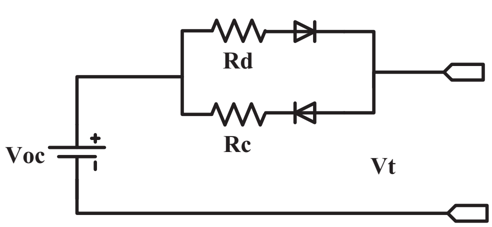


**Fig. 10.** Modified Thevenin battery model 3.

## 3. Thevenin-based battery models

In this section, seven Thevenin-based models of a battery will be described briefly as follows.

### 3.1. Thevenin battery model

Transient behavior of the battery has not been investigated in the previous models. Thevenin battery model is composed of an ideal voltage source ($V_{oc}$), an internal resistance ($R_{int}$), an over-voltage resistance ($R_1$) and a capacitor ($C_1$). The configuration of this model is shown in Fig. 7a. $C_1$ and $R_1$ show the capacity of parallel plate and the resistance implicated by the contact resistance of the plate respectively. The major shortcoming of the Thevenin battery model is that all the parameter values are assumed to be constant, while all the parameter values are related to the SOC, storage capacity of the battery, discharge rate, temperature and some other characteristics of discharge. The application of this model is in hybrid power train modeling where the battery is combined with fuel cell/ultra capacitor energy storage shown in Fig. 7b [27,28].

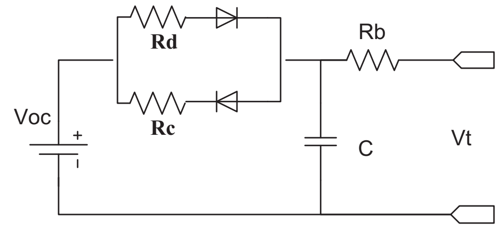


**Fig. 11.** Modified Thevenin battery model 4.

### 3.2. Modified Thevenin battery model 1

Thevenin model has been improved using a linear electrical battery model shown in Fig. 8 [29]. This model is better than previous ones because the behavior of the battery during over-voltage and self-discharge of the battery is considered. Although it is more accurate than previous models, the changes of the parameter values according to different operating conditions in previous models have been ignored. In this model, $R_p$ is self-discharge resistance, and $C_4$ is electrochemical capacitance of the battery cell. $N_m$ which is the battery cell overvoltage network consists of resistances of $R_1$, $R_2$, $R_3$ and capacitors of $C_1$, $C_2$, and $C_3$. These parameters are given based on the measured electrical response of the battery. Furthermore, $V_{oc}$ is the open circuit voltage of the battery. This model is utilized for transient and steady state analysis of electrical systems working with batteries.

### 3.3. Modified Thevenin battery model 2

This model takes the transient behavior of a battery consists of an RC parallel network ($R_1$ and $C_1$ are overvoltage resistance and double layer capacitance respectively) for the transient behavior of a cell, and an ohmic resistance $R_{int}$ for the instantaneous voltage drop shown in Fig. 9a. The battery runtime cannot predict in this model as well. The DC response of the battery cell cannot be modeled. The open circuit voltage, $V_{oc}$, relates to the SOC [30]. Voltage sag is defined as a short reduction in effective voltage of a bus-bar. It is often created through short circuit, overloading, and starting of large electrical motors. Dynamic voltage resistor (DVR), shown in Fig. 9b, is a FACTS device applied to remedy the sag of the voltage. It consists of a battery and pulse width modulation (PWM) inverter. This model is applied in the DVR system [17] as well as in photovoltaic systems [31].

### 3.4. Modified Thevenin battery model 3

This modified simple battery model (shown in Fig. 10) is a compound of an ideal voltage source connected to two series of internal resistance. They consist of discharging and charging resistances. As this figure shows, $R_d$ and $R_c$ are the internal resistances of the discharging and charging mode respectively. Both these resistances consume energy. Therefore, they express energy losses containing both electrical and non-electrical losses. The diodes in the model are supposed to be ideal. They are applied to bypass internal resistances during charging or discharging cycles. Both charging and discharging cycles do not conduct simultaneously. The conducting diode is forwardly biased and the other diode is reversely biased. It is supposed that the diodes have no interpretation. They are just to clarify the difference between the charge and discharge resistance. Dependency on

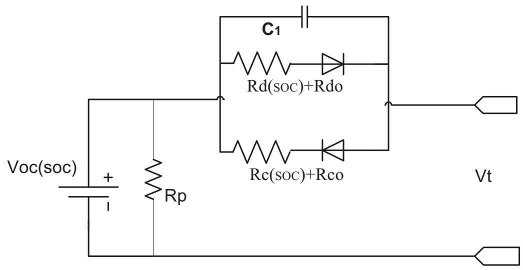


**Fig. 12.** Modified Thevenin battery model 5.

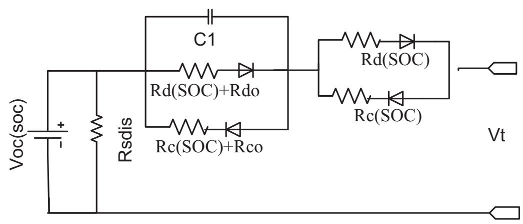


**Fig. 13.** Modified Thevenin battery model 6.

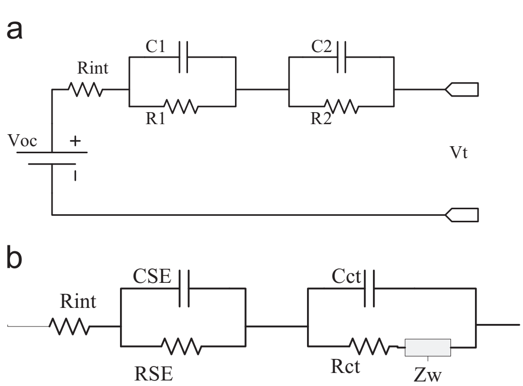


**Fig. 14.** (a) Impedance battery model. (b) The battery equivalent internal impedance.

the SOC is not considered in this model, hence the main disadvantage of this model. All the elements in this model are linear, and this is yet another disadvantage. This model is implemented in electric/hybrid vehicles simulations [32].

### 3.5. Modified Thevenin battery model 4

This battery model, alias reactive circuit model, is similar to the model described in modified Thevenin battery model 3 and presented in [32]. The dynamic electrical equations of the circuit model for charging and discharging cycles are obtained as follows:

$$\frac{dV_p}{dt} = -V_p\frac{1}{R_dC} + V_{oc}\frac{1}{R_dC} - I_b\frac{1}{C}, \quad V_p \le V_{oc} \tag{7}$$

$$\frac{dV_p}{dt} = -V_p\frac{1}{R_cC} + V_{oc}\frac{1}{R_cC} - I_b\frac{1}{C}, \quad V_p > V_{oc} \tag{8}$$

where

$$I_b = \frac{V_p - V_{oc}}{R_b}$$

$V_{oc}$ is the open circuit voltage; $V_p$ is capacitor voltage and $V_t$ is the terminal voltage of the battery. $R_c$, $R_d$ and $R_b$ are the charging, discharging and the internal resistance of the battery respectively; $C$ is the polarization capacitance of the battery and $I_b$ is current of the battery. In this circuit model portrayed in Fig. 11, the SOC of the battery can be easily computed under open circuit voltage i.e. when $R_b=0$, $V_t=V_p$. Both of them converge exponentially toward $V_o$ with a time constant concluded by $R_d$. This model is applied in electric or hybrid vehicles simulations.

### 3.6. Modified Thevenin battery model 5

All the elements of this model relate to the state of charge shown in Fig. 12. The elements' characteristics are described below

Self-discharge resistance ($R_p$): This resistance is a function of the open circuit voltage. It concerns for resistances in:

(a) Electrolysis of water in the battery at high voltage.
(b) Slow leakage of the battery terminal at low voltage.

Charge and discharge resistances ($R_c$ and $R_d$): These relate to electrolyte resistances, plates and fluid resistance; however, all these resistances can be different in charging and discharging cycle and rate.

Overcharge and over discharge resistance ($R_{co}$ and $R_{do}$): These are the internal resistances that will be changed when the battery is overcharged or over discharged. There is a capacitor in the model which explains the battery transient behavior [33]. This model is applied in electric or hybrid vehicles simulations too.

### 3.7. Modified Thevenin battery model 6

This model, shown in Fig. 13, is an improvement of the previous battery models i.e. modified Thevenin battery model 5. It contains nonlinear characteristics. It is dependent on the state of charge. The elements of this model are the functions of the state of charge or the open circuit voltage which dependent on the state of charge. This model consists of a series of experimental tests performed through examination of the graphic plots of the experimental data, and manufacturers' specifications. Two ideal diodes have been implemented to recognize between overvoltage resistance and internal resistance for charge and discharge cycles [30]. Because this model is a developed version of the previous one, it has been implemented in electric or hybrid vehicles and trains simulations [33,44].

## 4. Impedance-based battery models

Impedance-based model is another electrical model shown in Fig. 14a. The impedance elements in this model are clarified using electrochemical impedance spectroscopy (EIS) measurements to achieve the AC response of a cell at certain frequency spans. The results are depicted on a chart named Nyquist diagram. This chart consists of a real axis representing the resistance of the cell and the imaginary axis representing the reactance of the cell. Each point in this area is stated with the impedance response at a specific frequency. This is mostly performed using implementation of a small-amplitude sinusoidal current or voltage signals to the system and checking the response for different frequencies. The reason for using this method is to keep the system in the linear region. Then, the response will have the sinusoidal shape and so likely with different amplitudes and phase angles. The internal impedance of the battery which is dependent on the electrochemical processes in the cell is modeled in Fig. 14b known as Randle circuit. In this model, $R_{int}$ is the bulk resistance, describing the electric conductivity of the electrodes and the separator. $R_{SE}$ and $C_{SE}$ are the symbols of resistance and capacitance of the surface film layer on the electrodes. $R_{ct}$ is the charge transfer resistance. It relates to the charge transfer between electrode and the

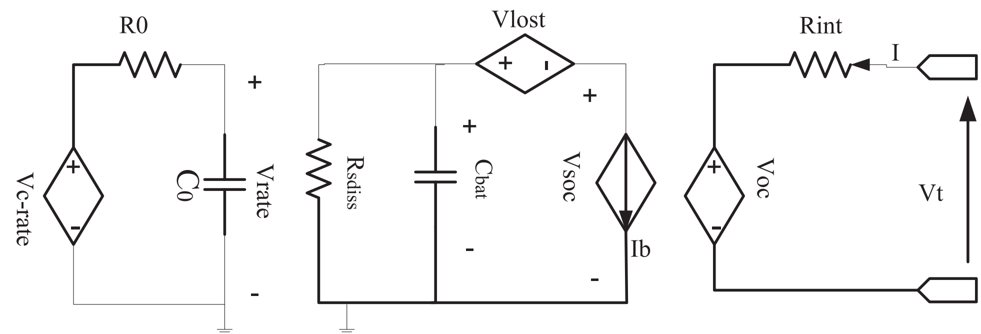


**Fig. 15.** Runtime-based model.

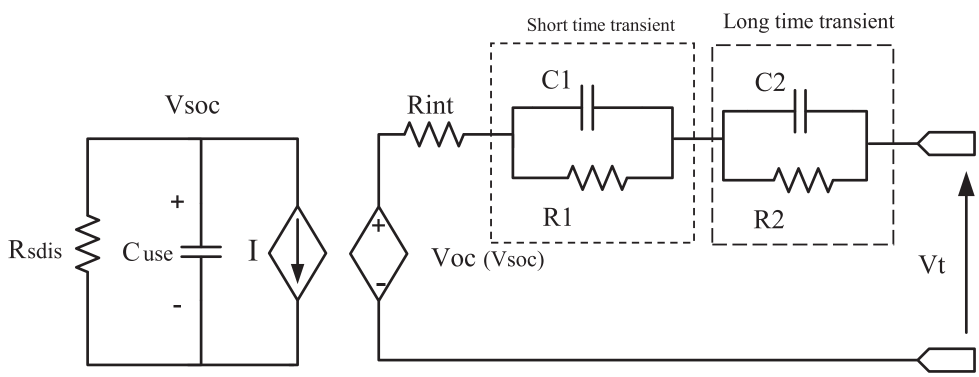


**Fig. 16.** Combined electrical circuit-based model.

electrolyte. $C_{dt}$ is double layer capacitance between the electrode and electrolyte. $R_{ct}$ and $C_{dt}$ demonstrate the medium frequency response. $Z_W$ is designated as the Warburg impedance. In the lithium ions battery, the diffusion of the lithium ions between the electrolyte and active material is presented using this impedance at the low frequency response. RC pair is implemented to increase the accuracy of the model. Thus, it can be replaced with a resistance when accuracy is not very important. Furthermore, in some cases an inductance is joined to a series bulk resistance for explaining the positive reactance response at high frequencies. Likewise, the positive reactance response can be neglected [34–38]. This model can be applied to traction electric/hybrid vehicles modeling and simulation.

## 5. Runtime-based battery model

The equivalent circuit of battery cell, shown in Fig. 15, is called runtime-based circuit model. It is a complex model for simulation of runtime and DC response under a constant discharge current. It can be modeled for a limited transient response [39]. In this model, the following effects are considered: (1) the voltage of the battery is dependent on the SOC. When the battery is discharged, $V_t$ diminishes by a varied rate; (2) the battery's actual capacity is dependent on discharge rate. Conversion of chemical energy into electrical one diminishes by increasing rate; (3) total charge quantity is affected by discharge current frequency. This model consists of three separated circuits. The left circuit indicates the dependency on discharge frequency. It consists of $R_0$, $C_0$, and $V_{c\text{-rate}}$. $R_0$ and $C_0$ are transient elements. They are referred to as charge storage resistor and charge storage capacitor respectively. They created a low pass filter in order to control $V_{lost}$. The middle circuit indicates the dependency on the state of charge and discharge rate. It consists of $V_{lost}$, $C_{bat}$, $R_{sdis}$ and current source of $I_b$. $V_{lost}$ indicates the dependency on discharge rate. It diminishes the charge of the battery and controls the output voltage. The magnitude of $V_{lost}$ is a function of the discharge rate. It is modeled using a look up table. $C_{bat}$ and $R_{sdis}$ are battery capacitor and self-discharge resistor respectively. Finally, the right circuit consists of an open circuit voltage ($V_{oc}$), and internal resistor of the battery ($R_{int}$). This model has been applied to traction electric/hybrid vehicles modeling.

## 6. Combined electrical circuit-based model

This model, shown in Fig. 16, is a combination of the Thevenin, impedance and runtime-based electrical circuit models. It consists of two separate parts: energy balance and voltage response circuits. The first part models the capacity of the cell, the amount of energy remaining in the battery cells, the self-discharge, and the battery runtime. The capacity of the battery is indicated by Cuse. The Cuse is not an actual capacitance. The voltage of $V_{SOC}$ changes between 0 and 1, tantamount to the battery state of charge. Thus, the SOC will be utilized instead of $V_{SOC}$. It changes (increases or decreases) depending on the charge or discharge current respectively. Self-discharge of the battery is modeled by a resistor shown by $R_{sdis}$. The second part (voltage response) explains how battery voltage changes to a given load current ($I$). Open circuit voltage is a dependent supply voltage which depends on the state of charge, presented by $V_{SOC}$. $R_{int}$ is the Ohmic resistance of the battery. It consists of the bulk resistance $R_b$ and surface layer resistance $R_{SEI}$. $R_1$ and $C_1$ are the symbols of the short time constants in the voltage response. They are dependent on the charge transfer resistance ($R_{ct}$) and double layer capacitance ($C_{dl}$). The long time constants are shown by $R_2$ and $C_2$, connected to a single RC pair Warburg impedance in order to model diffusion phenomena

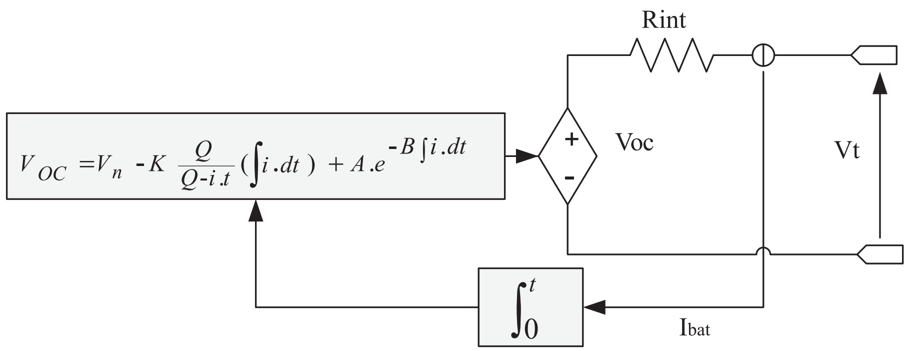


**Fig. 17.** Generic battery model.

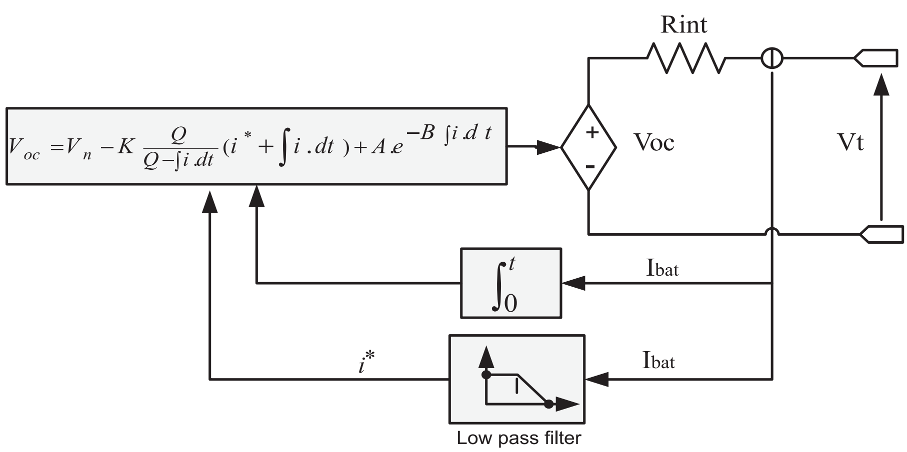


**Fig. 18.** Modified generic battery model.

[39,40]. This model can be implemented in simulating a traction system or in electric/hybrid vehicle modeling.

## 7. Generic-based model

### 7.1. Generic battery model

A generic battery model consisting of a controlled voltage source connected to a resistance can be applied for modeling of various types of electrochemical batteries. This model is shown in Fig. 17. The model's parameters can be obtained from the manufacturer's discharge curve. This model is easy to use. It can be implemented to simulate a type of battery using dynamic simulation software such as Matlab/Simulink. In this model, state of charge of the battery can be implemented as a state variable for avoidance of the mandatory loop problem [41].

Based on Fig. 17, the equation is obtained from shepherd equation. The shepherd equation model is given as follows:

$$V_{oc} = E_0 - K\frac{Q}{Q-\int i\,dt} i - R_0 i \tag{9}$$

where $E_0$ is open circuit voltage of the battery, $Q$ is capacity of the battery, $K$ is polarization resistance coefficient, $R_0$ is internal resistance, and $i$ is battery current. There is a nonlinear term in the shepherd equation i.e. $Q/(Q-\int i\,dt)$.

This term states how the voltage is varied by real charge and current of the battery. In order to eliminate the algebraic loop, the shepherd equation is modified as in the following equation:

$$V_{bat} = E_0 - K\frac{Q}{Q-it} i + A\cdot \exp(-B\cdot it) \tag{10}$$

In this model, the following suppositions are implemented:

The internal resistance of the battery does not change during the charge and discharge. Pukert effect and temperature on battery capacity are not included. The memory effect and self-discharge of the battery are ignored.

### 7.2. Modified generic battery model

A modified generic battery model is shown in Fig. 18. It is a modified model of the previous one. It presents the charge and discharge cycle of the battery using the following equations based on the Shepherd equation [42]:

$$V_{dis} = E_0 - K_{dr}\frac{Q}{Q-it} i^* - R_0 i - K_{dv}\frac{Q}{Q-it} it + \mathrm{Exp}(t) \tag{11}$$

$$V_{ch} = E_0 - K_{cr}\frac{Q}{it+\lambda Q} i^* - R_0 i - K_{cv}\frac{Q}{Q-it} it + \mathrm{Exp}(t) \tag{12}$$

where $Q$ is battery capacity. $k_{dr}$ and $k_{cr}$ are the polarization resistance coefficient at discharge and charge cycles respectively. $k_{dv}$ and $k_{cv}$ are the polarization over voltage coefficient at discharge and charge cycles respectively. In the second term of Eqs. (11) and (12), the polarization Ohmic voltage drops are different for charge and discharge cycles. They are modified using filtered battery current ($i^*$) to simulate the dynamic response of the real slow voltage at step current response. The $\lambda$ in Eq. (12) is used to shift the polarization resistance during the charge cycle of the battery. The third term in the above equations refers to internal resistance for charge and discharge cycles. The fourth term of the equation is added to this term with respect to the polarization overvoltage. This term, accompanied by $E_0$, can better describe the nonlinear open circuit voltage relationship with the state of charge. The Exp($t$) term explains an exponential dynamic voltage to bring a nonlinear hysteresis

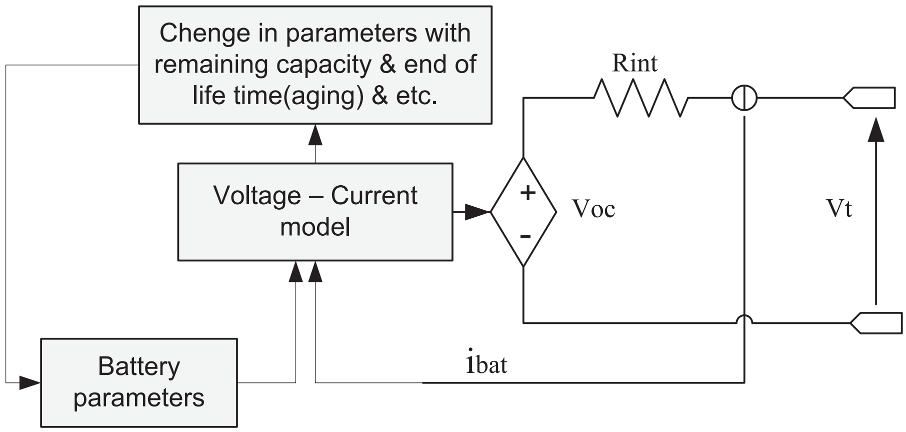


**Fig. 19.** Generic battery model with changes in parameters.

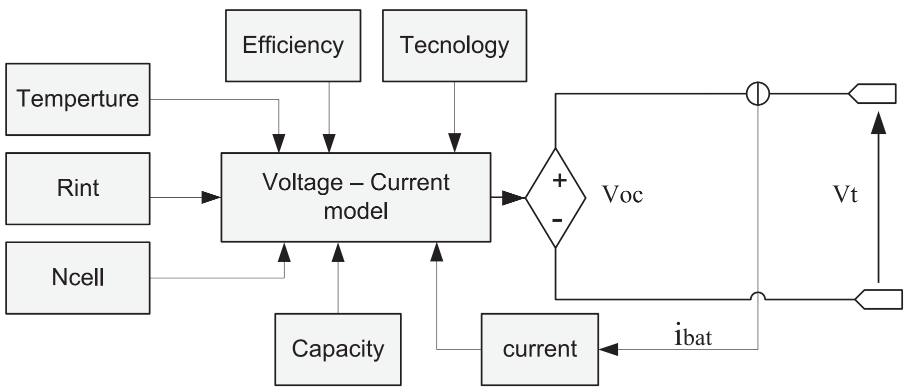


**Fig. 20.** Another generic battery model.

phenomenon between charge and discharge cycles [42]. Eqs. (11) and (12) can be revised by using state of charge. Eq. (13) shows that when the state of charge decreases, the voltage drops, and polarization overvoltage impact increases in the discharge cycle. In addition, with regard to (13), the polarization overvoltage impact is negligible in the proximity of the full battery capacity but becomes a predominant part as the state of charge collapses:

$$V_{\mathrm{dis}} = E_0 - K_{\mathrm{dr}}\frac{1}{SOC}i^* - R_0 i - K_{\mathrm{dv}}\left(\frac{1}{SOC} - 1\right) + \mathrm{Exp}(t) \tag{13}$$

Capacity of the battery does not vary with the current. The temperature effect is neglected in this model. Also, battery aging has not been considered. The self-discharge is not entered. These factors can be obtained in a more complete mathematical model of the battery shown in Fig. 19. The battery parameters vary during the lifetime of the battery to supply an ageing profile and many other agents affect battery performance [42]. Parameters required for the mathematical modeling of the battery can be obtained based on the characteristics of the battery manufacturer. One approach is to build a parameter derive system which is established upon equations extracted from critical points of the characteristics in steady state. Afterwards, the model parameters can be achieved resolving the system equations. Another way is getting model parameters through regression method. Another generic model is shown in Fig. 20. The model consists of several blocks representing various sectors of the battery. Each block has various equations for each technology. The suitable equations are chosen based on a specific technology. The internal resistance of the cell, ambient temperature, number of cells, capacity, efficiency and other similar indices are represented by the input blocks. This model can be implemented in any simulations [43]. These models have been applied to an electric/hybrid vehicle modeling and simulation.

## 8. Conclusion

In this paper, electrical circuit modeling of batteries was classified into six main types of models consisting of (a) simple models, (b) Thevenin-based models, (c) impedance-based models, (d) runtime-based circuit models, (e) combined electrical circuit-based models, and (f) generic-based models. The electrical circuit models are implemented in dynamic simulation studies such as wind energy conversion systems, photovoltaic systems, and electric/hybrid vehicles systems. The Thevenin models have a good transient response in a significant SOC and in a constant $V_{oc}$; however DC response and the battery runtime predictions are not adequately carried out. Although some components have been augmented to the models in order to improve these defects (such as utilization of a variable capacitor), the runtime error, voltage error and complication increase. The effects of temperature and SOC variations have not been generally considered in this model. They are suitable for transient studies but AC response is limited. Impedance-based model uses electrochemical impedance spectroscopy and complex impedance $Z_{ac}$ to fit the impedance spectra. The fitting mechanisms have a difficult and complicated process. The ambient temperature and SOC variations have been ignored in this model too. The AC response has been modeled well but transient response is limited. The DC response and battery runtime prediction have not been considered. The runtime-based model is utilized to simulate the DC voltage response and runtime of a battery in a constant discharge current. This model is complex. It is

not suitable for the prediction of DC voltage response and runtime when the discharge current changes. Thus, it is not accurate as a model in AC response and its transient response is limited. Combined-based model consists of a blend of Thevenin, impedance, and runtime-based models. It is capable to predict the DC voltage response, runtime and transient response simultaneously. This model is more accurate and more comprehensive than other models. Finally, a generic battery model is an accurate and general model implemented in the modeling of different battery technologies. This model has been included in Simulink demo (Simpower system) as a part of hybrid/electric vehicles simulations.

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